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**SUPERCONDUCTING DETECTOR OF  
NUCLEAR PARTICLES**

**by**

**Donald Edward Spiel**



# United States Naval Postgraduate School



## THESIS

SUPERCONDUCTING DETECTOR OF NUCLEAR PARTICLES

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Donald Edward Spiel

October 1969

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Superconducting Detector of Nuclear Particles

by

Donald Edward Spiel  
A.B., University of California Los Angeles, 1960

Submitted in partial fulfillment of the  
requirements for the degree of

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#### ABSTRACT

The response of thin, superconducting films of tin and of indium to alpha particle bombardment has been studied. The films were sufficiently thin and narrow that individual alpha particle impacts initiated superconducting to normal transitions across a full film cross section. The transitions were observed by means of the IR drop produced by a transport current. For low current densities, self-terminating voltage pulses of a few nanoseconds duration were observed. At higher current densities, a normal region initiated by an alpha particle propagated, by Joule heating, to the ends of the film. The alpha-particle range exceeded the thickness of the films and the energy deposited in the substrate by an alpha traversal affected the response of any film in direct contact with its substrate. Thin, thermally insulating films introduced between the detectors and their substrates, however, effectively isolated the detectors. The variation of count rate with film current was studied and is shown to be consistent with the variation of critical current density along the length of the film. A heat diffusion model accounts for the observed behavior of the thermally isolated films.

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## I. INTRODUCTION

This paper reports the results of experiments in which some of the transient effects on superconductors of nuclear particle bombardment were examined. The work owes its impetus to suggestions made by Sherman [1,2] and the earlier work of Andrews, et.al.[3]. Preliminary results were published elsewhere [4].

In particular, we have bomarded thin, superconducting films of tin and of indium with 5.3 Mev alpha particles and have measured the effective radii of the regions driven normal by the incident alpha particles. The films were sufficiently thin and narrow that the energy deposited by individual alpha particles initiated superconducting to normal transitions across a full film cross section. The transitions were observed, in turn, by means of the IR drop produced by a transport current. It is not necessary that the alpha particle, of and by itself, drive normal a complete section of the film in order for its effect to be observed. The remainder of the film will switch if the transport current is such that the critical current density is exceeded in the unswitched portion of the film, see Fig. 1. Indeed, the effective radii have been defined in terms of the ratio of the critical currents with and without bombardment.

A variety of rectangular films ranging in width from 5 to 50 microns and in thickness from 500 to 2000 $\text{\AA}$  were evaporated onto either glass or crystalline quartz substrates. For low current densities, self-terminating voltage pulses of a few nanoseconds

duration were observed. At higher current densities, normal regions initiated by alpha particles were observed to spread to the ends of the film by Joule heating.

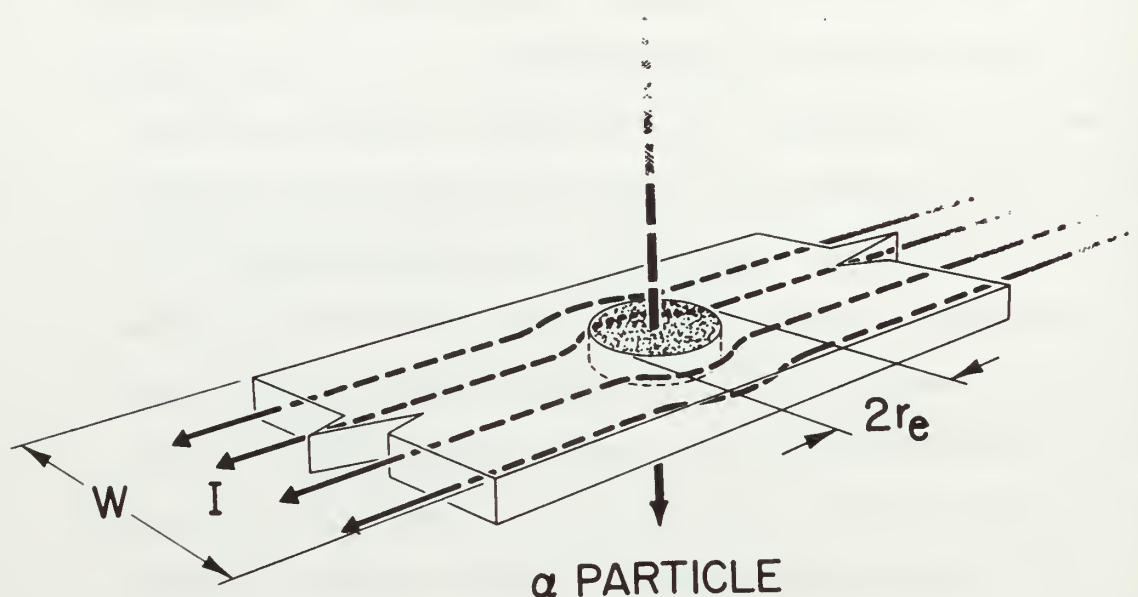


Fig. 1. Presumed Current Paths in a Superconducting Thin Film Following an Alpha Particle Traversal.

Film thickness were less than the range of the alpha so that energy was deposited in the substrate as well as in the film. In the case of crystalline quartz, ballistic phonons carried enough energy back into the film to substantially increase the effective radii. The insertion of a thin film of electron-polymerized-oil varnish between the detecting film and its substrate succeeded in thermally isolating the detector.

Computer solutions of the heat diffusion equation in terms of the effective radii are in good agreement with the measured values for both indium and tin on glass and thermally isolated quartz

substrates. The manner in which the count rate varies with current is consistent with calculations based upon the variation of critical current density along the length of the film and lends credence to the manner in which the radii have been measured.

The thin films used in these experiments were made with a high impurity concentration ( $\sigma \approx 10^6$  mho/cm at  $4^\circ\text{K}$ ) for both tin and indium, so that a relatively short  $4^\circ\text{K}$  electron transport mean free path of about 0.1 micron resulted. The observed radius of the region heated above the superconducting critical temperature was of the order of 5 microns. Thus, the mean free paths involved were small enough to make classical heat flow calculations reasonable if perhaps marginal. Such calculations were employed, however, because of their simplicity.

The chronology of events which is the basis for the view just described began with a pre-experimental picture which went as follows: When an ionizing particle traverses matter, it loses the bulk of its energy by electronic excitation with little of the primary energy given to the lattice. It was assumed, initially, that the excited electrons would rapidly share their energy with the lattice so that, in effect, the temperature of all the material, lattice as well as electrons, would be immediately raised in some region surrounding the path of the particle. It seemed likely that if the bombarded material was in the superconducting state, then this thermal spike would drive normal a region about the axis of the spike and the event could be detected in the manner described above.



The first experiments were performed with crystalline quartz-backed tin films which were about 30 microns in width. When these films were bombarded with alpha particles, individual alpha events were readily observed. But when the experimentally determined radii were compared to the theoretical radii predicted on the basis of a classical heat diffusion calculation, the agreement was poor. The measured radii were much larger than anticipated by these simple calculations.

A new hypothesis was put forth in which it was assumed that the energy imparted to the electrons was not being shared with the lattice for times at least as long as that characterizing the event. In this calculation, still based upon classical heat flow, the lattice contributions to the specific heat and thermal conductivity were excluded. The radii predicted by this model were, surprisingly, in excellent agreement with those measured.

In these early models, the assumption had been made that the thermal relaxation rate between the film and substrate was too small for the substrate to be involved in the formation of the nanosecond pulses. There was evidence cited in the literature [5,6] to support this assumption. In this view, radii and pulse characteristics should have been independent of the substrate material. However, when, as a test of this assumption, glass-backed films were studied, the results were substantially altered. The critical radii were smaller than those for the quartz-backed films and approached the radii expected for the lattice included case.



In order to examine the extent of substrate involvement, experiments were performed in which pairs of closely spaced parallel films were evaporated onto glass and quartz substrates. The films were electrically independent and thermally connected only through the substrate. If, as was then expected, the substrate heat was increasing the radius of the region driven normal, then for such closely spaced narrow films one would expect to observe coincident pulses from the two films. In fact, a significant fraction of the events observed were coincident; and, as a consequence, it was evident that the assumption of total film-substrate independence was invalid.

At this juncture the thin varnish layers were introduced between the films and their substrates. Calculations had suggested that the introduction of this acoustic impedance mismatching layer could reduce the transmission of incident phonon energy by more than an order of magnitude. And, indeed, with these layers the rate of coincidences for the twin films was greatly reduced, and the effective radii decreased to the values expected if the lattice is included.

Finally, these experiences coupled with studies of the manner in which the count rate varies with film current and how this is related to critical current density variations along the film has led to a useful, self-consistent model of the process. These and other details of the experiments are discussed in the following sections in greater detail.

## II. EXPERIMENTAL TECHNIQUES AND APPARATUS

### A. DETECTOR PREPARATION

The detectors were manufactured by evaporation of the film material through razor blade masks onto glass or crystalline quartz substrates. The substrates were 1/8-in. thick by 1-in. diameter cylinders with the parallel surfaces optically polished to 40/20. In the case of crystalline quartz, the faces of the disks were perpendicular to the C-axis so that maximum thermal conductivity to the bath was achieved. Prior to the deposition of the film, the substrates were ultrasonically scrubbed in a detergent solution, vapor degreased and rinsed in distilled water.

Film deposition was accomplished in a Veeco VE-400 evaporator which had been modified by the addition of an upper base-plate. The evaporations generally began at a pressure of  $10^{-6}$  torr and increased to about  $3 \times 10^{-6}$  torr during the deposition which occurred at a rate of about  $20 \text{ \AA sec}^{-1}$ . These pressures and slow deposition rates resulted in film resistivities of around  $10^{-6}$  ohm cm. Such relatively high values, indicating impure and imperfect films, were desirable from the standpoint of detection sensitivity. Tin films were evaporated onto substrates held at  $0^{\circ}\text{C}$  and indium onto backings at  $-80^{\circ}\text{C}$  which were the respective maximum substrate temperatures which produced smooth, pin-hole free films.

Insulating films were made by the electron bombardment technique described by Christy [7]. In this method, the insulating film is formed through the polymerization, by electron

bombardment, of the backstreaming diffusion pump oil which impinges on the substrate surface. Insulating film thicknesses, which in these experiments were always  $300\text{\AA}$ , were determined from bombardment time, at constant current, after interferometric calibration.

A Sloan Instrument Corporation deposit thickness monitor was used to determine detector film thicknesses. This device monitors the film deposition by recording the shift in frequency of a crystal-controlled oscillator as evaporant mass condenses on the crystal. Calibration was accomplished by relating frequency shifts to thickness as measured with a Fabry-Perot interferometer. Widths and lengths were measured with a microscope equipped with a micrometer eyepiece and calibrating stage. The widths recorded were averages of several readings taken over the length of the films. Deviations from the mean were seldom in excess of  $\pm 1.5$  microns.

In the experiments which required pairs of closely spaced, parallel films, the films were evaporated simultaneously through a razor blade mask. The central portion of these films was masked by a fiber made by drawing a thread from Ducco cement.

#### B. SAMPLE PROBE

The customary problems of cooling samples to very low temperatures were compounded in these experiments by the requirement that the detectors be bombarded by alpha particles. Alpha spectrum degradation was undesirable and, as a result, it was necessary to

evacuate the region between the detector and the alpha source. Cooling, therefore, could be accomplished only indirectly, and this constraint placed a premium on minimizing heat leaks into the sample.

The probe is shown in position in Fig. 2. The vacuum line was thin-walled stainless steel tubing through which passed the electrical leads and a concentric alpha-source positioning rod. This rod, also thin-walled stainless, was thermally shorted to the helium bath by braided copper at multiple points along its length. The alpha source could be positioned at distances to the sample ranging from 0.3 to 3 cm. At the upper limit of its travel a spring loaded door closed cutting off the alpha beam to the sample.

Electrical contact was made to the sample by means of miniature 50 ohm coaxial cables which were thermally connected to the bath by passing through 15 cm of tight fitting copper sleeves which were in contact with the bath. For studying the switching characteristics of the films, fast rising pulses from a 50 ohm source were employed. It was necessary, therefore, to terminate some of the cables at the sample end with a non-inductive, temperature independent, 50 ohm resistor. This resistor was constructed from 0.001-in. diameter nichrome wire which replaced the final 1.5 cm of the central conductor of the coaxial cable to be terminated.

The probe was evacuated through a valve and a Veeco quick disconnect. Indium "O" rings provided cold-end vacuum seals and functioned reliably at all temperatures. That heat leaks to the

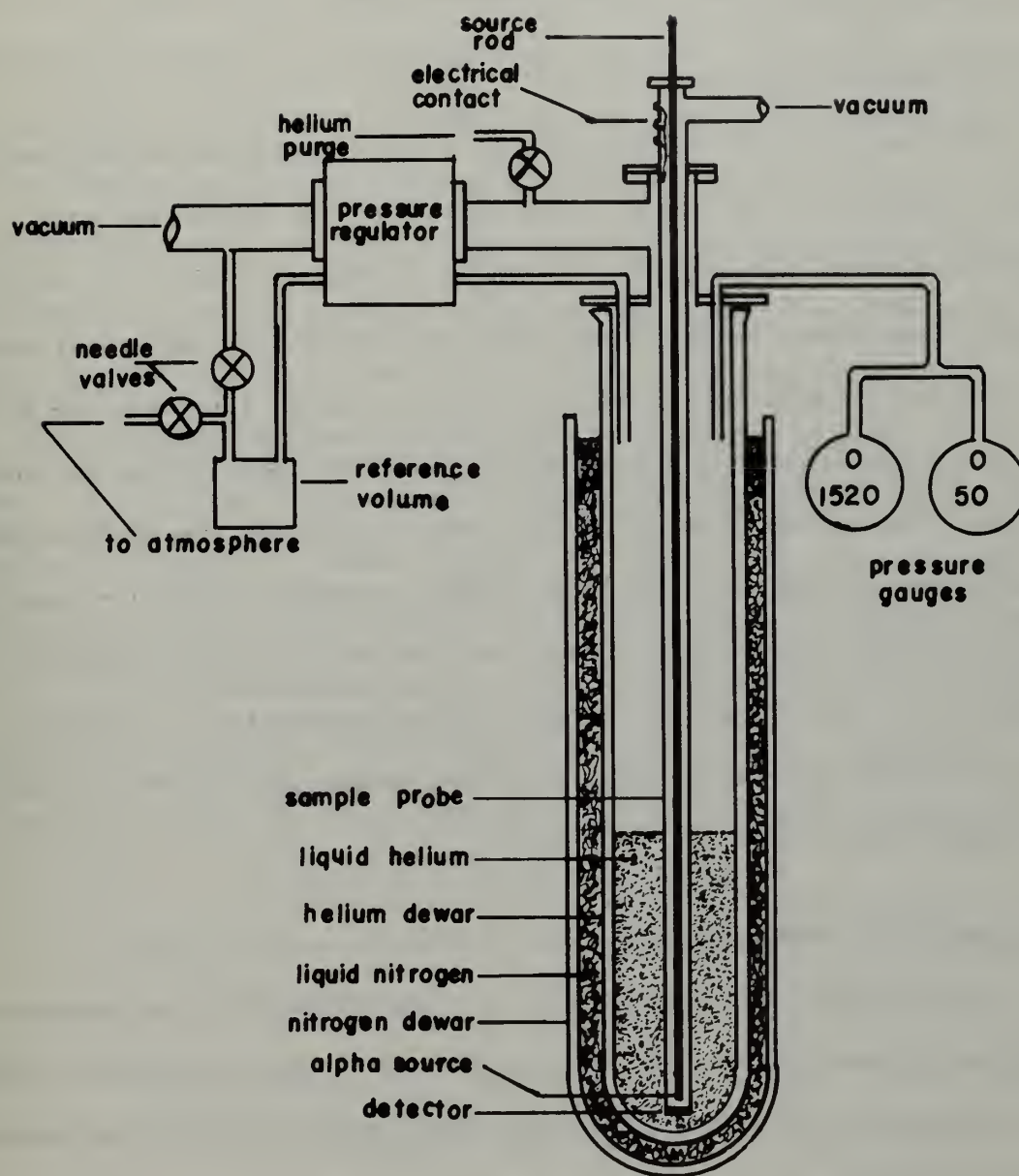


Fig. 2. Schematic of Dewar and Related Apparatus



detector were not significant was demonstrated by the fact that transition temperatures were unaffected by the addition of an exchange gas into the vacuum chamber and were close to the values reported by others for tin and indium films.

### C. CRYOGENIC APPARATUS

The temperatures of interest in these studies were confined to the region 1.9 to 4.2°K. The apparatus for achieving and measuring these temperatures is shown in Fig. 2. A 4-in.-ID by 43-in. long glass helium dewar and associated nitrogen dewar were housed in an explosion-proof enclosure and each was provided with a 1/2-in.-wide slit in its radiation shield for monitoring the helium level. The helium vapor pressure and, therefore, temperature were controlled by pumping with a fore pump through a pressure regulator which provided continuous control of the helium vapor pressure to within  $\pm 0.5$  torr over the range of bath temperatures utilized. A pair of Wallace and Tiernan pressure gauges were used to measure the vapor pressure.

### D. ELECTRICAL MEASUREMENTS

In the course of this work, a variety of electrical measurements were made on over 30 different films. Most parameters studied were examined with respect to their dependence on bath temperature. In the following paragraphs the quantities of interest will be defined and the measurement techniques described.

An important characteristic of a film is its so-called dc critical current,  $I_c$ , which has been defined as the current at

which the resistance of a film abruptly increases from near zero to nearly its normal state value as the current is slowly increased from zero. It is temperature dependent and except for the temperature region near the transition, where the critical current densities are low, is a well defined quantity. The abrupt increase in resistance at  $I_c$  is the result of the propagation along the film of the boundaries of the initial resistive region. It is at this current that Joule heating in the resistive region just exceeds the heat lost by the region to its surroundings [8]. The heat was often sufficient to destroy a film so that provisions were made for rapidly cutting off the current whenever propagation began. A plot typical of the voltage (and hence resistance) variation with current is shown in Fig. 3. That  $I_c$  is not, in general, the current at which the first resistance appears is demonstrated in Fig. 3. The current at which the first measurable resistance appears has been termed the threshold current,  $I_t$ .  $I_c$  and  $I_t$  characterize the film alone and were defined without reference to and measured in the absence of alpha bombardment.

It has long been established that  $I_c$  is characteristic of only one segment of a film and that other portions of the film have higher critical currents [9]. Later, in discussing the variation of count rate with current it will be important to distinguish between the critical current at one point from that at another so that  $I_c(x)$  will then be written for the critical current at some point  $x$  along the film. Then,  $I_c$ , as defined above is the minimum critical current and will be designated  $I_c(0)$ .

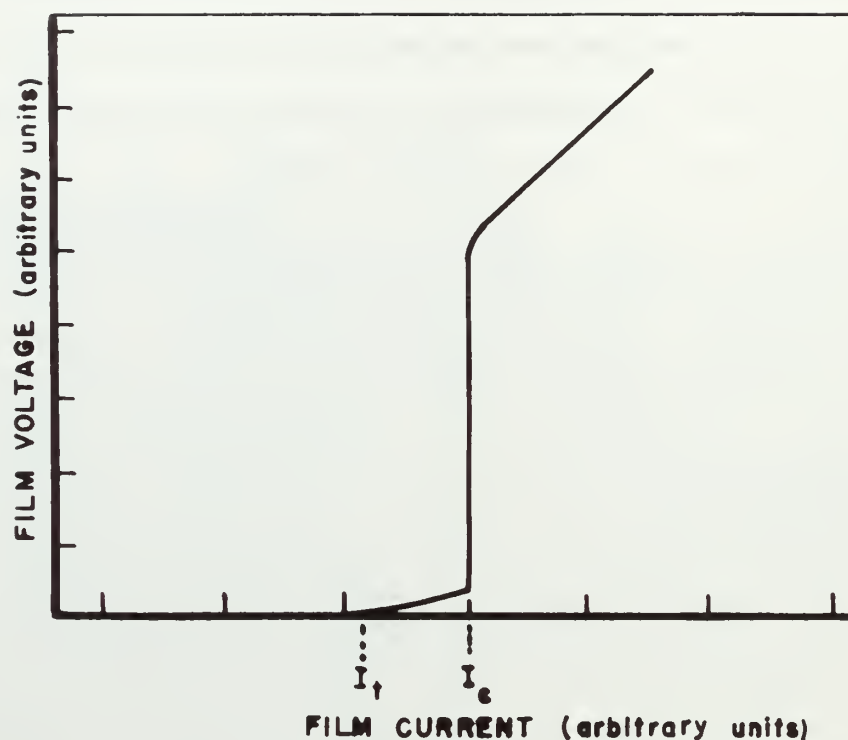


Fig. 3. Variation of Film Voltage with a Slowly Increasing Current.

Finally, the minimum current at which an alpha-particle induced event can be observed has been called the alpha onset current and is designated  $I_a(x)$ . It is, as indicated, a function of position along the film and, as with  $I_c$ , the minimum  $I_a(x)$  will be written  $I_a(0)$ . It has not been possible to measure  $I_c(x)$  or  $I_a(x)$  in the sense that to each specific point on the film a critical current can be assigned. Rather, an attempt was made to determine what fraction of the total film length has had its critical current exceeded at any given current. Hence,  $x$  is a number which varies between zero and the length of the film; and  $I_c(0)$  or  $I_a(0)$  are the currents at which an infinitesimal length of a film has had its critical current exceeded. It is in this vein that these expressions are written below.



In a typical experimental run the quantities of interest were the low temperature normal state resistance, the transition temperature and the variation with temperature of  $I_C(x)$  and  $I_A(x)$ ....  $I_C(x,T)$  and  $I_A(x,T)$ . A block diagram of the electronics used to make these measurements is shown in Fig. 4. The switches shown are not actual switches, but are alternate ways of routing the respective signals through BNC connectors. The letters at each "switch" pole indicate the connection made when the detector was connected between the terminals with the same labels.

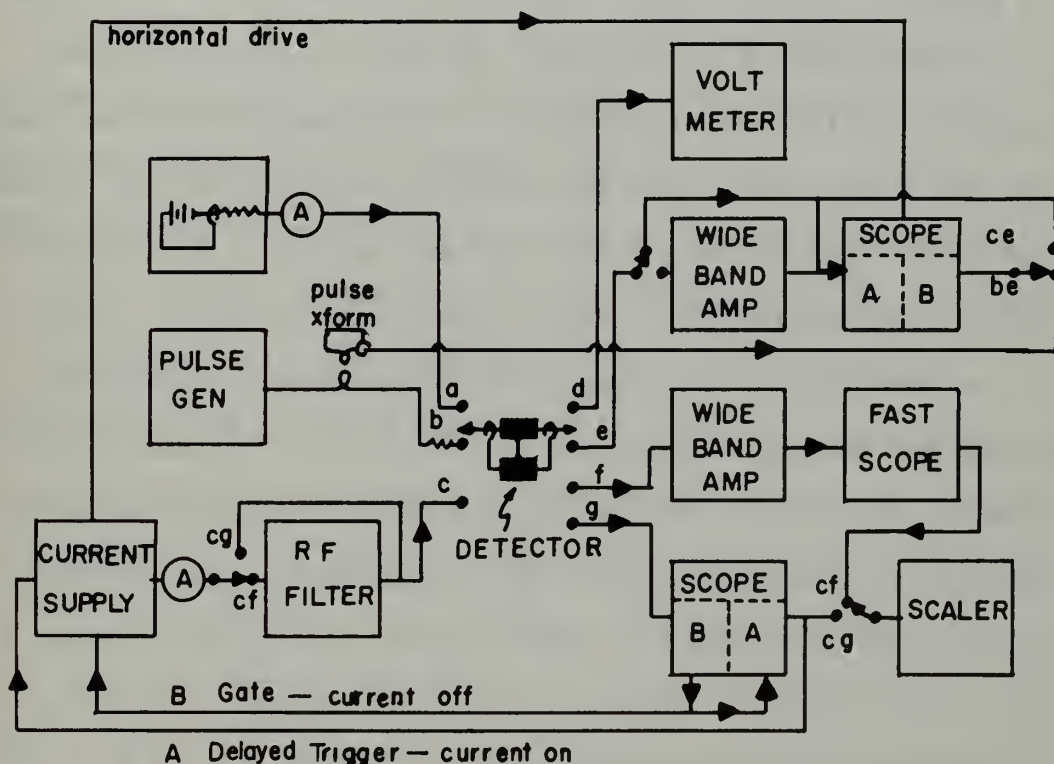


Fig. 4. Block Diagram of Electronics for Routine Measurements.

Normal state resistances and transition temperatures were measured by the usual four-terminal technique with the detector connected between the "a" and "d" terminals in Fig. 4. A 100 micro-ampere current was employed and voltages measured with a Keithley model 149 millimicrovolt meter.

The determination of  $I_c(x)$  was a two step process. First, with the detector between terminals c and e,  $I_c(0)$  was measured by slowly increasing the dc current until propagation occurred. To protect the film from burning out, the voltage across the sample was monitored on an oscilloscope which was set to trigger at a predetermined voltage. The gate voltage was fed into the current supply where an enabling, bistable multivibrator was triggered, cutting off the current. The remainder of the function  $I_c(x)$  was determined, with the detector between b and e, by applying a series of fast rising ( $\leq 1$  ns) current pulses to the film and observing the variation of film voltage with current. Film current was monitored with a Tektronix CT-2 current transformer driving one beam of a dual beam oscilloscope. Voltage was displayed on the other beam and the two traces were photographed together in families in which the current made step increases.

$I_a(x)$  was determined by measuring the variation of alpha particle count rate with film current. For the self-recovering pulses this was accomplished with the detector between c and f. The self-recovering pulses were typically a few hundred microvolts in amplitude and of the order of nanoseconds in duration at low currents. Noise was about 50 microvolts RMS and originated at the input of

the amplifier. To count the pulses, a Keithley model 107 wide-band pulse amplifier was used to drive a Tektronix model 585 oscilloscope in which the sweep trigger level was set to discriminate against the noise. The scope gate voltage was used to drive the scaler. As the current was increased, the self-recovering pulses approached the propagation level with a consequent increase in their duration. In order to preclude a single pulse from triggering successive sweeps, under these conditions, a dead time was introduced by the simple expedient of increasing the sweep length. Near propagation, the dead time was typically set to 10 milliseconds. Counting propagating pulses was somewhat more complex because of the necessity to momentarily switch off the detector current after each pulse in order to permit recovery of the film to the superconducting state. To do this, the detector was connected between terminals c and g, the RF filter was bypassed to insure rapid current switching, and the detector signal was fed directly to a dual beam scope. Preamplification was unnecessary because of the large pulse amplitudes. The pulses drove the lower beam of a Tektronix model 555 oscilloscope. The gate from this beam was used to switch off the detector current and also to trigger the upper beam. The delayed trigger from the upper beam turned the current back on after a delay determined by the setting on the delayed trigger and the sweep rate. This seemingly circuitous technique was necessary to insure that the lower beam was fully enabled before

current turn on, in order to preclude having the current on during a transient period when the electronics was unable to turn it off. Switching times were of the order of microseconds and dead times of the order of 100 milliseconds.

As discussed earlier, in the course of this study certain data indicated that heat deposited by the alpha particle in the substrate probably was influencing the detector response. This possibility was confirmed by an experiment in which two very closely spaced and very narrow detectors ( $\sim 10$  microns wide each, separated by  $\sim 5$  microns) were run simultaneously. A block diagram of the experimental arrangement is shown in Fig. 5. Pulses from the detectors were amplified independently and fed to a dual-beam scope, one to the upper beam and the other to the lower, the sweep of which was slaved to the upper beam, as shown. The probability of both films being hit simultaneously was extremely remote so that coincidence pulses had to have been motivated by a common source; viz, the substrate. The results, to be discussed in some detail later, clearly indicated that the substrate was involved.

The threshold current,  $I_t$ , was measured by observing a trace of film voltage versus current on an oscilloscope as the current was increased on a ramp and the horizontal was driven by an output from the current generator. The detector was between terminals labeled c and e, and the voltage sensitivity was of the order of micro-volts per cm.

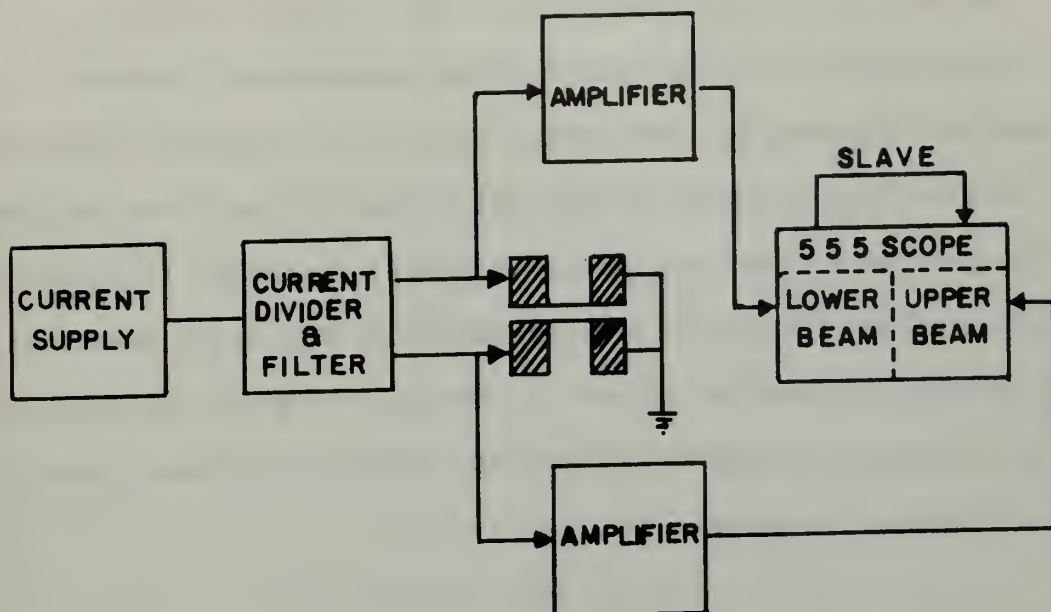


Fig. 5. Diagram of the Circuitry Used in the Twin Film Coincidence Experiments

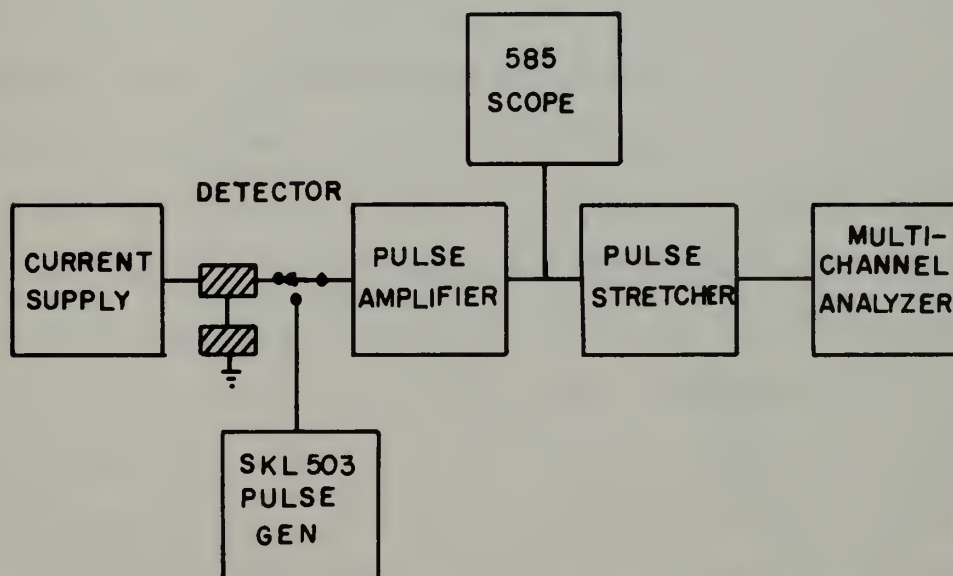


Fig. 6. Block Diagram of Pulse Height Analyzing Equipment. The Pulse Generator and Oscilloscope Were Used for Calibration.

One of the interesting features of the self-recovering pulses was that under any given condition of temperature, current, and alpha particle energy, the pulses were not of constant amplitude. To measure this spread, the circuit shown in Fig. 6 was employed. The pulses were first amplified by a Keithley model 107 amplifier, then stretched [10] before being fed to an RCL 512 channel analyzer. The pulses were monitored with a Tektronix 585 oscilloscope and calibration was accomplished with the 585 as a standard and an SKL 503 pulse generator.



### III. RESULTS

Among the superconducting materials available as potential particle detectors, only tin and indium have been examined. These materials were attractive because they had convenient transition temperatures and because films of these elements were easily produced. Some of the physical and electrical characteristics of a representative sample of the films tested are listed in Table I.

An example of the resistance transition into the superconducting state, typical of all films examined, is shown in Fig. 7. The critical temperatures observed for tin were somewhat above the bulk value of  $3.72^{\circ}\text{K}$ , presumably because of tensile stresses [11]. Many workers have observed similar shifts. In these experiments care was always exercised to keep the alpha flux low enough to avoid generalized heating of the film or its substrate. Thus, as illustrated in Fig. 7, the transition temperatures of the films were constant with or without alpha bombardment.

The variation of the critical currents with temperature of several detectors is shown in Figs. 8 through 10. These results are typical of all the films examined, and have been chosen to illustrate the changing pattern with increasing film width. That the reduced currents were due to the alpha bombardment and to no other cause was evidenced by the fact that the count rate varied inversely with the square of source-detector separation, going to zero when the alpha source was withdrawn completely, and remaining at zero when the source holder, without source material, was reinserted to the same position. Self-recovering pulses were observed

TABLE I. PHYSICAL CHARACTERISTICS OF SELECTED FILMS

| No. | Film<br>Mat'l | Subs<br>Mat'l             | Note                    | Width<br>( $\mu$ )  | Lgth<br>(mm)      | Thick<br>( $\mu$ ) | $\frac{\rho(300)}{\rho(4.2)}$ | $\rho(4.2)$       | $T_c$             |
|-----|---------------|---------------------------|-------------------------|---------------------|-------------------|--------------------|-------------------------------|-------------------|-------------------|
| 4   | Tin           | Quartz                    | -                       | 49.8                | 4.77              | 0.100              | 13.4                          | 1.08              | 3.82              |
| 6   | Tin           | Quartz                    | -                       | 30.5                | 4.95              | 0.100              | 17.6                          | 0.73              | 3.81              |
| 8   | Tin           | Quartz                    | -                       | 21.4                | 4.65              | 0.100              | 17.6                          | 0.78              | 3.80              |
| 9   | Tin           | Quartz                    | -                       | 10.2                | 4.43              | 0.100              | 15.6                          | 0.92              | 3.77              |
| 12  | Tin           | Glass                     | -                       | 53.8                | 4.28              | 0.105              | 16.4                          | 0.87              | 3.75              |
| 14  | Indium        | Glass                     | -                       | 58.9                | 5.16              | 0.100              | 20.7                          | 0.51              | 3.42              |
| 22  | Indium        | Quartz                    | -                       | 34.1                | 1.82              | 0.100              | 18.5                          | 0.69              | 3.40              |
| 29  | Tin           | Quartz                    | Side 1<br>Gap<br>Side 2 | 6.1<br>6.7<br>12.7  | -<br>1.60<br>-    | -<br>0.100<br>-    | -<br>-<br>-                   | 1.56<br>-<br>1.24 | 3.83<br>-<br>3.83 |
| 30  | Tin           | Glass                     | Side 1<br>Gap<br>Side 2 | 9.5<br>6.4<br>9.6   | -<br>1.60<br>-    | -<br>0.100<br>-    | -<br>-<br>-                   | 1.58<br>-<br>1.48 | 3.86<br>-<br>3.86 |
| 31  | Tin           | Quartz<br>with<br>Varnish | Side 1<br>Gap<br>Side 2 | 10.0<br>1.9<br>15.0 | 0.99<br>-<br>0.90 | -<br>0.100<br>-    | 11.1<br>-<br>11.1             | 1.58<br>-<br>1.67 | 3.80<br>-<br>3.80 |
| 34  | Indium        | Quartz<br>with<br>Varnish | Side 1<br>Gap<br>Side 2 | 7.1<br>2.1<br>5.8   | 1.35<br>-<br>1.41 | -<br>0.100<br>-    | 19.1<br>-<br>19.5             | 0.63<br>-<br>0.58 | 3.41<br>-<br>3.41 |
| 36  | Indium        | Quartz<br>with<br>Varnish | -                       | 16.4                | 1.14              | 0.200              | 16.2                          | 0.71              | 3.35              |
| 39  | Tin           | Quartz                    | -                       | 17.5                | 0.31              | 0.205              | 17.4                          | 1.26              | 3.79              |



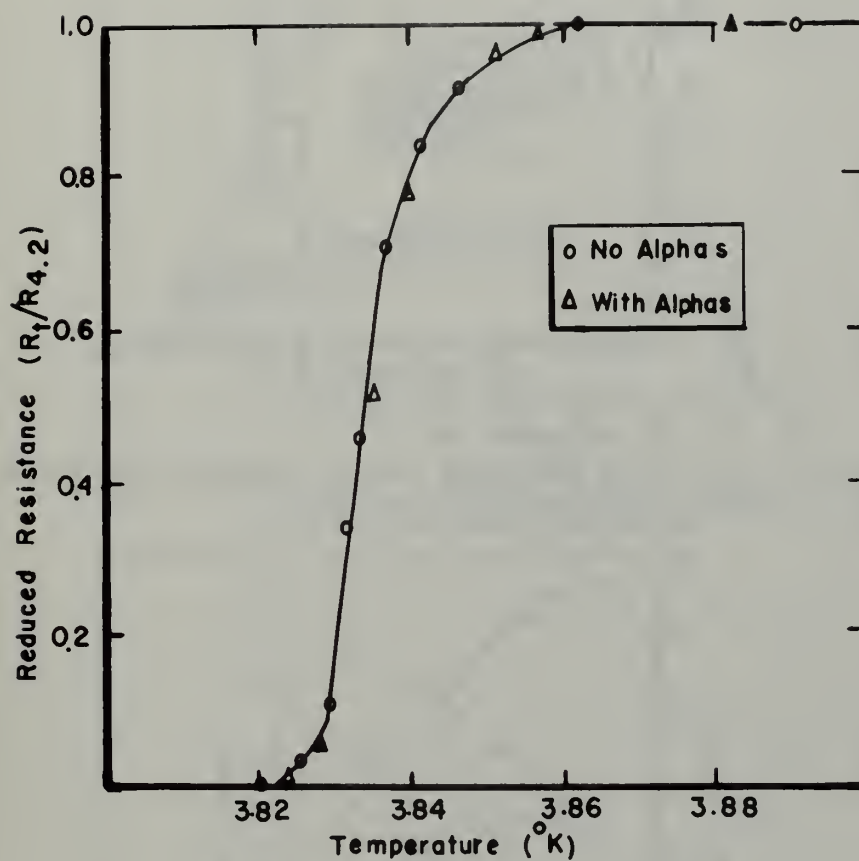


Fig. 7. Reduced Resistance Versus Temperature With and Without Alpha Particle Bombardment.

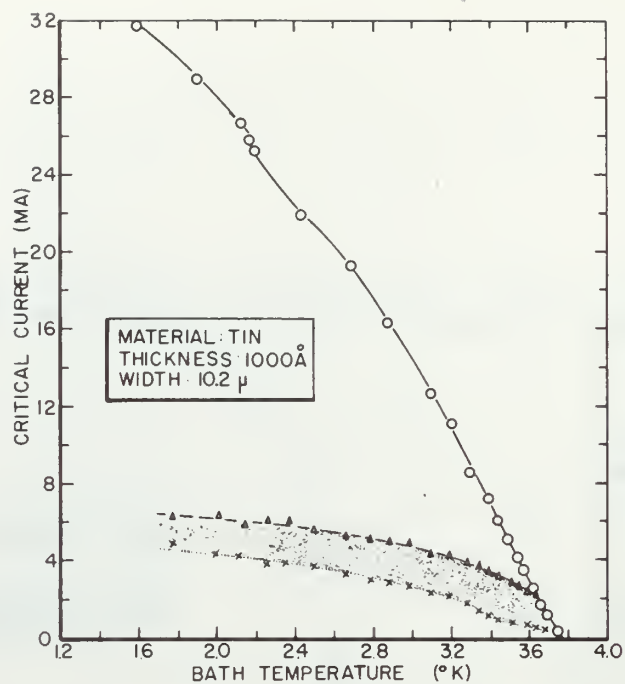


Fig. 8. Critical Currents Versus Temperature for a 10.2 Micron Wide Tin Film

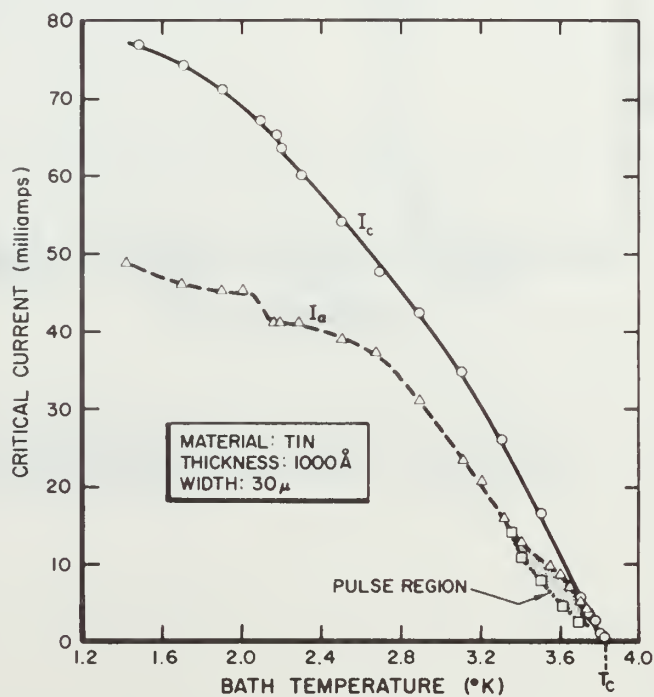


Fig. 9. Critical Currents Versus Temperature for a 30.5 Micron Wide Tin Film

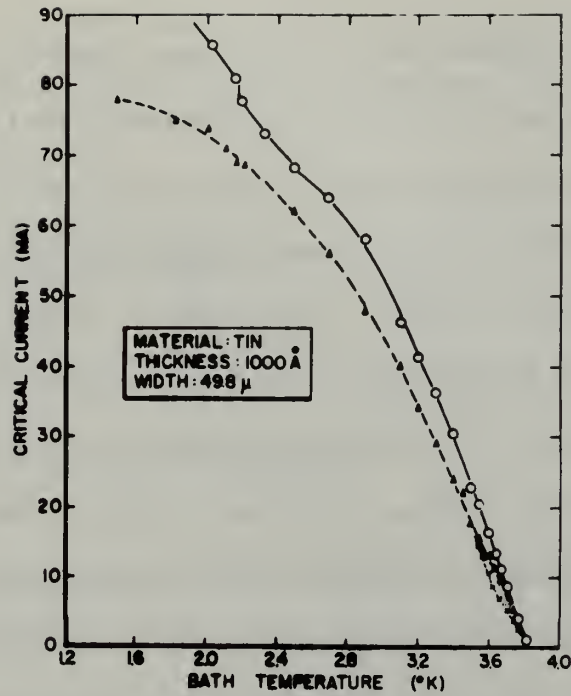


Fig. 10. Critical Currents Versus Temperature for a 49.8 Micron Wide Tin Film

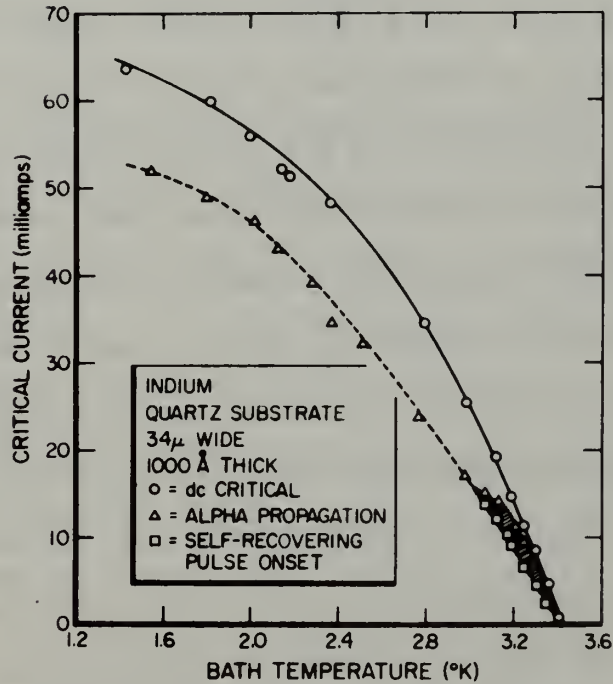


Fig. 11. Critical Currents Versus Temperature for a 34 Micron Wide Indium Film

in the shaded regions only. The lower boundaries of these regions define the current at which alpha pulses first appear. This current, as previously defined, is the alpha onset current,  $I_a(0)$ . Propagation occurs at the upper boundaries. In Fig. 8, where the ratio of critical radii to film width is large, it is seen that self-recovering pulses occur over the whole range of temperatures. As the film width is increased, however, the region of the self-recovering pulses narrows as shown in Fig. 9 where at temperatures of  $3.4^{\circ}\text{K}$  and below, the alpha onset pulses propagate. The process is further illustrated in Fig. 10 where the results from a still wider film are given. The behavior of indium films was similar, in every way, to the tin films, see Fig. 11.

For a given film, and at a particular temperature,  $I_a(0)$  was the lowest current at which the effects of the alpha-particle bombardment were observed and was the current at which the count rate was a minimum. As the film current was increased above  $I_a(0)$  the rate at which alpha pulses occurred also increased. As suggested earlier, this apparently was the result of differences in critical current along the length of the film. Thus, for any particular position along the film, say  $x'$ , there was a dc critical current  $I_c(x')$  and this segment of the film was sensitive to an alpha traversal only when the film current was equal to or greater than  $I_a(x')$ . The effect of the alpha traversal was quite equivalent to a reduction of the effective width of the film at the point of impact. In fact,  $I_a(x)$  was interpreted as the critical current for

a film whose width, at the point  $x$ , had been reduced by  $2r_e$  where  $r_e$  was the effective radius of the region driven normal. The defining relation, then, is

$$\frac{I_a(x)}{W-2r_e} = \frac{I_c(x)}{W}$$

where  $W$  is the film width. Solving for  $r_e$  gives

$$r_e = \frac{W}{2} \left( 1 - \frac{I_a(x)}{I_c(x)} \right). \quad (1)$$

As a practical matter,  $r_e$  was determined from a particular set of critical currents; namely, the minimum critical currents. Thus, all the effective radii as recorded below were determined from

$$r_e = \frac{W}{2} \left( 1 - \frac{I_a(0)}{I_c(0)} \right).$$

This method of determining  $r_e$  could not be used in a temperature region within about  $0.1^\circ\text{K}$  below the critical temperature, where the critical currents were low, because the amplifier input noise precluded observation of the self-recovering pulses at onset. In this case, another method was used to estimate  $r_e$ . In this technique, the film current was increased until the pulses emerged from the noise and the radii were calculated from the pulse-heights in which  $v = 2rI/\sigma A$  where  $\sigma$  was film conductivity,  $A$  was the cross sectional area of the film and the length switched normal was taken as  $2r$ . The radii measured in these two methods are clearly not the

same, but a closer look at the details leads to an expectation that for sufficiently large currents (i.e., near propagation) it should be the case that  $r \approx r_e$ . And, in fact, in regions where the two methods overlapped this was the case.

Radii as determined by these methods and from data similar to that displayed in Figs. 8 through 11 are shown in Fig. 12 for tin films and Fig. 13 for indium. The upper most data points in the two plots were typical of the results obtained for films on bare, quartz substrates. The dashed curves, which fit these data very well, were the results of calculations, as mentioned earlier, in which the heat diffusion equation was solved without the inclusion of lattice contributions to either the specific heat or the thermal conductivity.

The remainder of the data were derived, as illustrated, from a variety of films on both glass and quartz substrates. In each case, however, the detector was insulated from its substrate by a  $300\text{\AA}$  thick insulating varnish layer. The reduction in size of the effective radii, their independence of film thickness, and the significant decline in the number of coincident pulses in twin film experiments attested to the effectiveness of the thermal shield. The solid curves in these figures are effective radii predicted by a computer solution of the diffusion equation in which the temperature and phase dependences of both electron and lattice specific heat and thermal conductivity were taken into account. In addition, the critical current density dependence on temperature



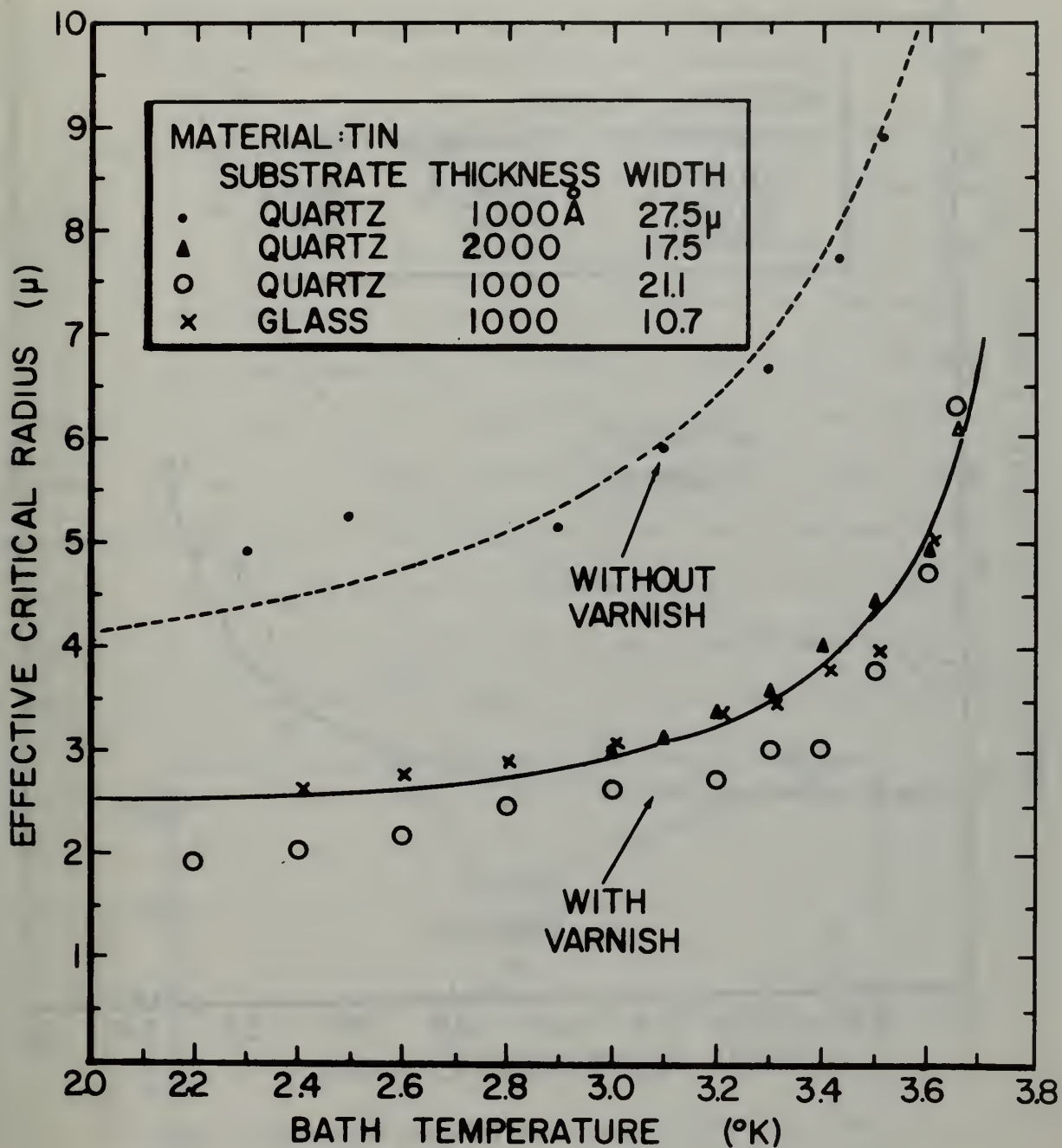


Fig. 12. Experimental and Theoretical Effective Radii for Tin

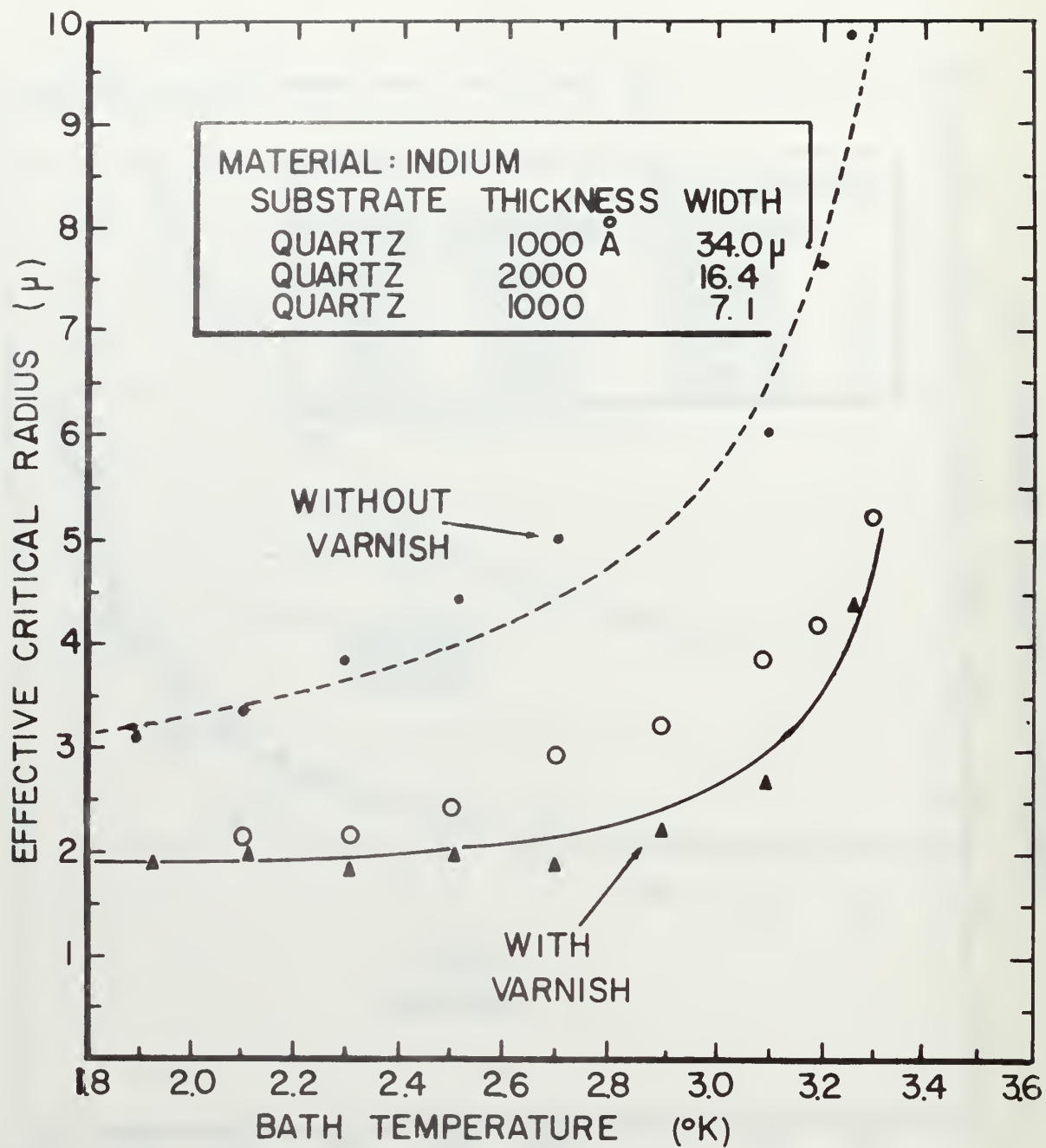


Fig. 13. Experimental and Theoretical Effective Radii for Indium



was included in order to account for the decreased current capacity in the superconducting, but heated, region adjacent to the normal core. The dc critical current temperature dependence was used for this purpose.

Studies were made of the count rate variation with film current and also of the manner in which the critical current varied along the length of the film. The measurements were difficult to make and their interpretation is open to some discussion. Nevertheless, a simple model was reasonably successful in correlating the data and this gave support to the method used to measure the effective radii. Figure 14 is a plot, typical of many, of the count rate variation with current for a tin film on an insulated quartz substrate. For currents above the alpha onset level, the sensitive area of the detector increased, and it was clearly reasonable to endeavor to invoke critical current variations as an explanation.

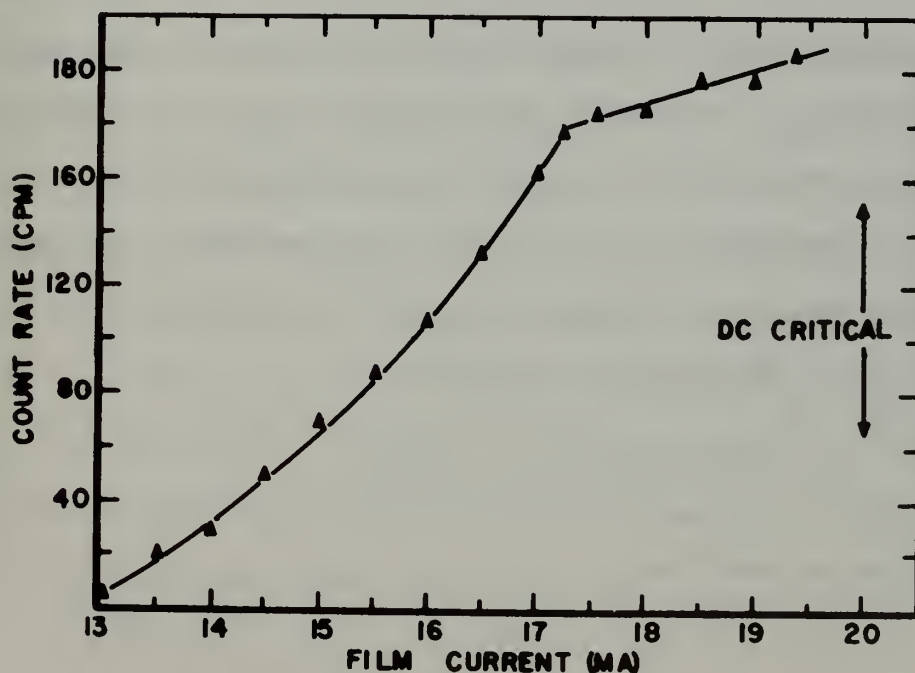


Fig. 14. Count Rate Variation with Current.

In this spirit, imagine a film of uniform width  $W$  and length  $\ell$  which is exposed to a flux of alpha particles  $\emptyset$  (particles per unit area per unit time). Assume that there is a known functional dependence by the critical current on position along the length of the film,  $I_c(x)$ . Assume, furthermore, that the detector is completely isolated from its substrate so that there is no exchange of heat; and suppose that every alpha impact results in a normal volume of radius  $r_e$ . Consider only cases where  $2r_e < W$  and, to expedite the calculation, make the simplifying assumption that with respect to heat flow (but not current) the films are infinitely wide. Thus, for this purpose, an alpha making an impact in the neighborhood of an edge will result in heat flow as if the edge didn't exist.

Examine, now, a film segment at a point  $x$  of length  $dx$  about  $x$  and which has a dc critical current  $I_c(x)$ . At a film current  $I_a(x)$  this segment will have just become sensitive to alpha impacts. Any alpha hitting at  $x$  within  $dx$  and within a lateral distance  $(W/2 - r_e)$  of the center will, by Equation 1, cause the critical current in the remainder of the segment to be exceeded. Increasing the current above  $I_a(x)$  increases the sensitive width of this segment until at a current  $I'_a(x)$  given by

$$I'_a(x) = I_c(x) \left( 1 - \frac{r_e}{W} \right)$$

the whole width is sensitive.

Thus, as the current increases from  $I_c(x)(W-2r_e)/W$  to  $I_c(x)(W-r_e)/W$  the sensitive width increases from  $(W-2r_e)$  to  $W$ . The net change in sensitive width is  $2r_e$  and the increase in current above  $I_a(x)$ , to change the sensitive width by this amount, is  $r_e I_c(x)/W$ . It is a simple matter to show that at a current  $I$  the sensitive width  $W_s$  is given by

$$W_s = W \left( \frac{2I}{I_c(x)} - 1 \right) + 2r_e \quad (I_a(x) \leq I \leq I_a'(x)) \quad (2)$$

The count rate dependence on current for this film segment will be

$$dc = \emptyset dA = \emptyset \left\{ W \left( \frac{2I}{I_c(x)} - 1 \right) + 2r_e \right\} dx \quad (3)$$

If the film current is increased from zero, counting will begin when the current reaches  $I_a(0)$ . Further increases in current will result not only in increasing the sensitive width at  $x = 0$ , but will cause additional segments (not necessarily adjacent to the segment represented by  $x = 0$ ) to begin counting as well. At  $I = I_a'(0)$  the full width at  $x = 0$  will be sensitive and there will be no further increases in count rate from this segment. At this current the full length of the film may or may not be involved in the counting process, depending on the nature of the function  $I_c(x)$ . Finally, at a current of  $I_a'(\ell)$  the total film will be sensitive and any further increase in current will not result in an increased count rate.

Since the relationship between the sensitive width of a film segment and film current is valid only over a restricted current range, care must be exercised to take the proper limits when integrating Equation 3. This results in a series of integrations with limits dictated by the requirement that Equation 2 be valid over the range of integration.

If the dc critical current is assumed to vary linearly with position, then integration of Equation 3 results in the following equations relating count rate to current which are applicable in the ranges indicated:

$$1) \quad c_I = \frac{\phi W l}{I_c(\ell) - I_c(0)} \left[ I \left\{ 2 \log \frac{I}{I_a(0)} - 1 \right\} + I_a(0) \right] \quad (4)$$

$$I_a(0) \leq I \leq \begin{cases} I_a(\ell) \\ I'_a(0) \end{cases} \text{ which ever is smaller}$$

$$2) \quad c_{II} = \frac{\phi W l}{I_c(\ell) - I_c(0)} \left[ I \left\{ 2 \log \frac{\eta'}{\eta} + \frac{\eta}{\eta'} \right\} - I'_a(0) \right] \quad (5)$$

$$I'_a(0) \leq I \leq I_a(\ell)$$

where  $\eta = (W - 2r_e)/W$  and  $\eta' = (W - r_e)/W$

$$3) \quad c_{III} = \frac{\phi W l}{I_c(\ell) - I_c(0)} \left[ 2I \log \frac{I_c(\ell)}{I_c(0)} - \eta (I_c(\ell) - I_c(0)) \right] \quad (6)$$

$$I_a(\ell) \leq I \leq I'_a(0)$$

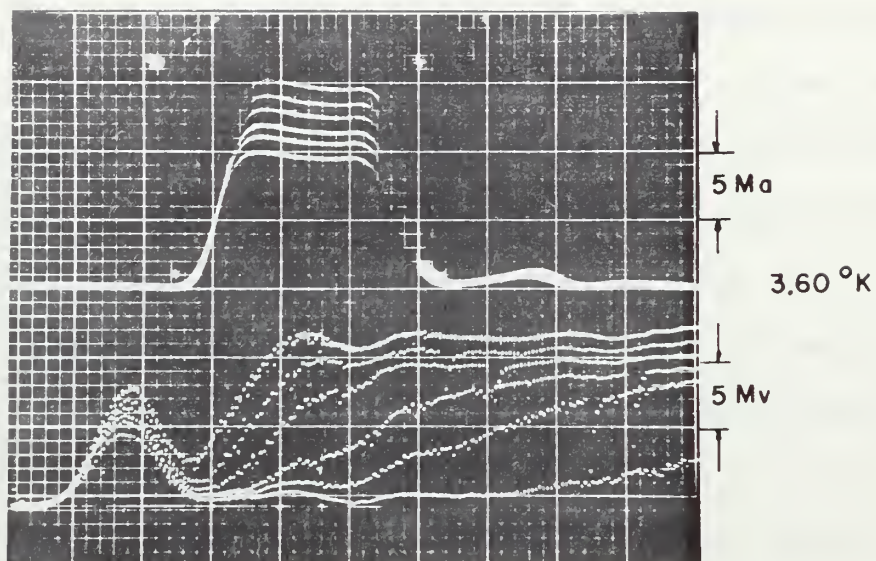
$$4) \quad c_{IV} = \frac{\phi W l}{I_c(\ell) - I_c(0)} \left[ I \left\{ 2 \log \frac{I'_a(\ell)}{I} + 1 + \frac{\eta}{\eta'} \right\} - I_a(\ell) - I'_a(0) \right] \quad (7)$$

$$\begin{cases} I_a(\ell) \\ I'_a(0) \end{cases} \leq \begin{cases} I'_a(0) \\ I_a(\ell) \end{cases} \leq I \leq I'_a(\ell)$$

For real films  $I_c(x)$  does not, of course, vary linearly with  $x$ . It is a function which can, however, be approximated by a series of linear segments sufficiently well that Equations 4 through 7 are useful. In addition, the film current can never exceed  $I_c(0)$  since at this current the film is normal (by propagation). In practice, this constraint placed a rather severe restriction on the range of currents over which the count rate could be observed, even after optimizing the effective radius to film width ratio for the particular temperature region of interest.

$I_c(x)$  was determined, as described above, by photographing a series of oscilloscope traces of the variation with time of both film current and film voltage as fast rising pulses were applied. Two such photographs are shown in Fig. 15 where the currents for the same film at two temperatures were displayed on the upper beams and film voltages on the lower. The current pulses applied to the film rose in about 1 ns. This does not show on the current traces which were displayed at the relatively slow rate of 20 ns/cm after the pulses had passed through an amplifier with a rise time of 13 ns; only amplitude information for the current pulses was desired. Vertical sensitivities were as indicated in the captions. The sweep rate for the voltage pulses was 2 ns/cm. The rise time of the pulses displayed was limited to 3 ns by the amplifier.





2 ns (lower traces)

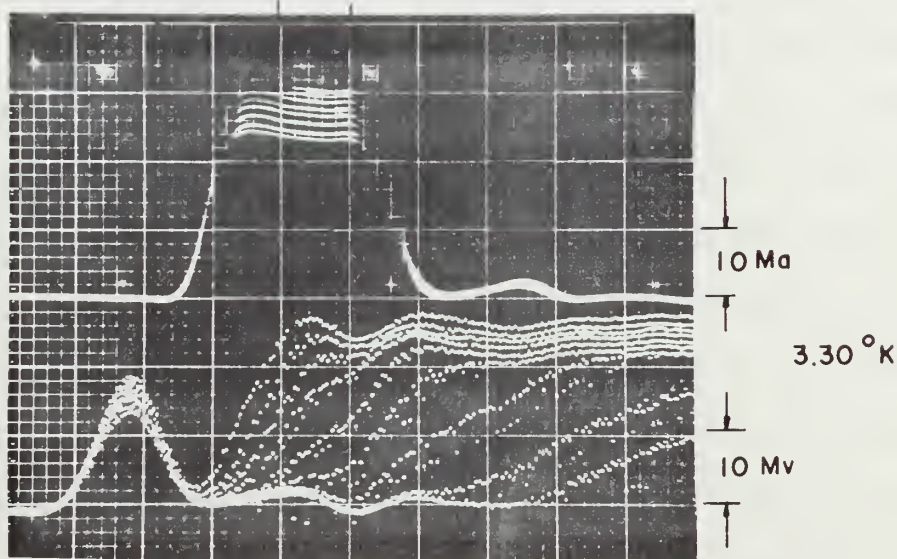


Fig. 10. Photographs of Oscilloscope traces of Film Current and Film Voltage Versus Time. (Upper Photograph with Film at  $3.60^{\circ}\text{K}$ ; and Lower Photograph with Film at  $3.30^{\circ}\text{K}$ .)

For this film, the dc critical currents,  $I_c(0)$ , were 7.6 and 18.9 ma at 3.60 and 3.30°K respectively. Taking the 3.3°K data as an example, in the lowest pair of traces, for which the current was 24 ma, very little of the film had switched within 15 ns of the arrival of the current pulse, which time was cursored by the inductive pulse preceding the resistance rise. As the current was increased, an increasing fraction of the film switched more and more rapidly until, at a current of about 32 ma, essentially the whole film was switching at a rate equal to or greater than the rate limitation imposed by the equipment. Just how much of the film has had its critical current exceeded at any given current can be, at best, only estimated from this kind of data. At currents in excess of  $I_c(0)$ , the film switches at multiple points along its length and each normal segment promptly begins expanding because of Joule heating. The expansion, or propagation, rates are sufficiently rapid that it is difficult to determine, at the current levels of interest, what fraction of a film has switched because its critical current has been exceeded and what fraction has switched because it is immediately adjacent to a switched region from which it is receiving heat.

Even in view of these difficulties, one thing is clear and that is that inspite of the fact that  $I_c(0)$  is 18.9 ma very little of the film has had its critical current exceeded up to a current not less than about 26 to 28 ma. Further increases in current, however, seem to involve an increasingly greater fraction of the



film. One is led, therefore, to suspect that if, indeed, the alpha onset current,  $I_a(0)$ , is to be associated with  $I_c(0)$ , then there should be little increase in count rate with current until the current reaches a value given by

$$I = I_a(x) = I_c(x) \left( 1 - \frac{2r}{W} \right) = 26 \left( 1 - \frac{2r}{W} \right)$$

at which point it should begin to increase rather sharply. This is, in fact, what actually happened, on this sample as well as others.

In general, if  $I_c(x)$  was taken as the current at which a fraction  $x$  of the film was normal within 4 ns of the time the film current  $I$  reached its maximum value, it could be employed in Equations 4 through 7 to predict with fair accuracy the count rate versus current relationships observed. A plot of  $I_c(x)$  derived from the oscilloscope traces shown in Fig. 15 for the 3.30°K case is shown in Fig. 16. Count rate versus current curves predicted by Equations 4 through 7 are compared to experimental results in Fig. 17. The knee in the curve at 3.60°K occurred at the current level where the whole length of the film had just become sensitive to bombardment. It continued to rise beyond the knee because the sensitive width was still increasing. The other curves would exhibit similar knees, and other structure as well, were it not for the limitation on film current which prevented counting above  $I_c(0)$ .

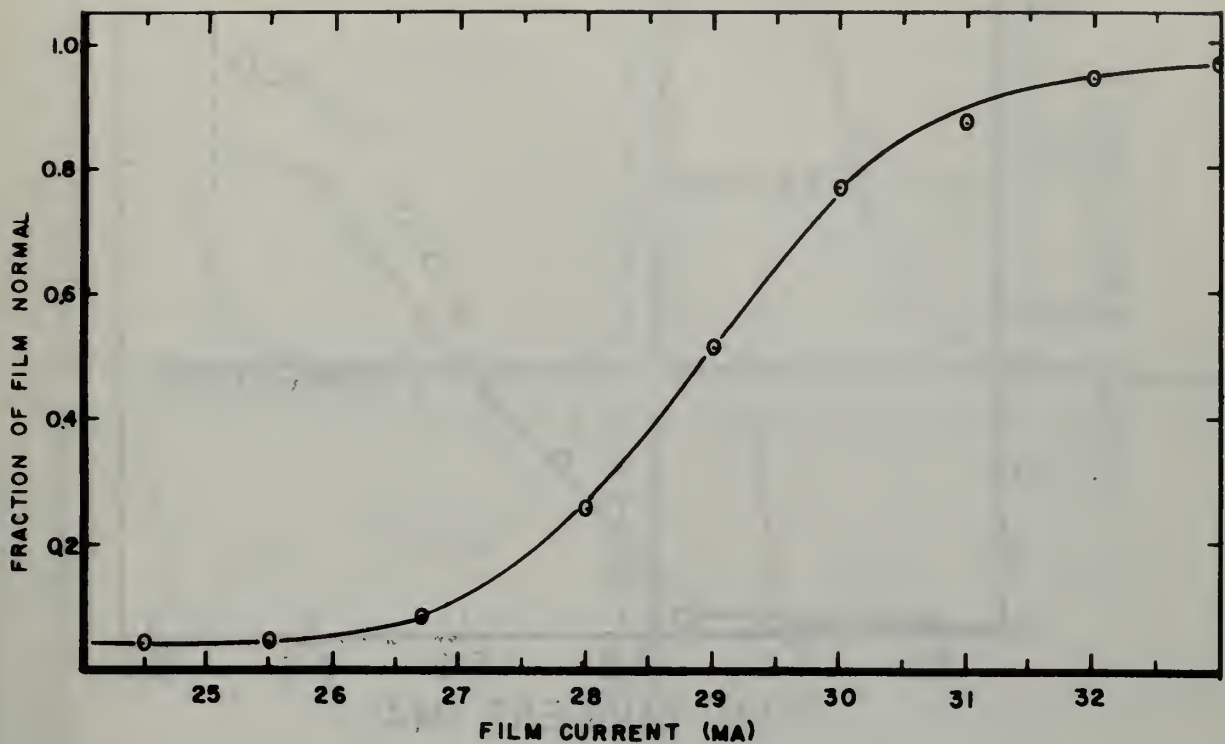


Fig. 16. A Plot of  $I(x)$  Derived from the Oscilloscope Traces Displayed in the Lower Photograph of Figure 15.

Thus, it is seen that this simple model coupled with the solutions to the diffusion equation for  $r_e$  can account reasonably well for the essential features of the count rate curves.

Finally, the results of a study of the distribution of amplitudes of self-recovering pulses is shown in Fig. 18. Here, the number of pulses,  $dn$ , per unit voltage increment,  $dv$ , is plotted against pulse voltage for several current levels. The contribution of amplifier noise to the spread is shown in Fig. 18f. The cause for the spread remains to be demonstrated, but it is inviting to speculate about the role that the variation of critical current along the film might play.

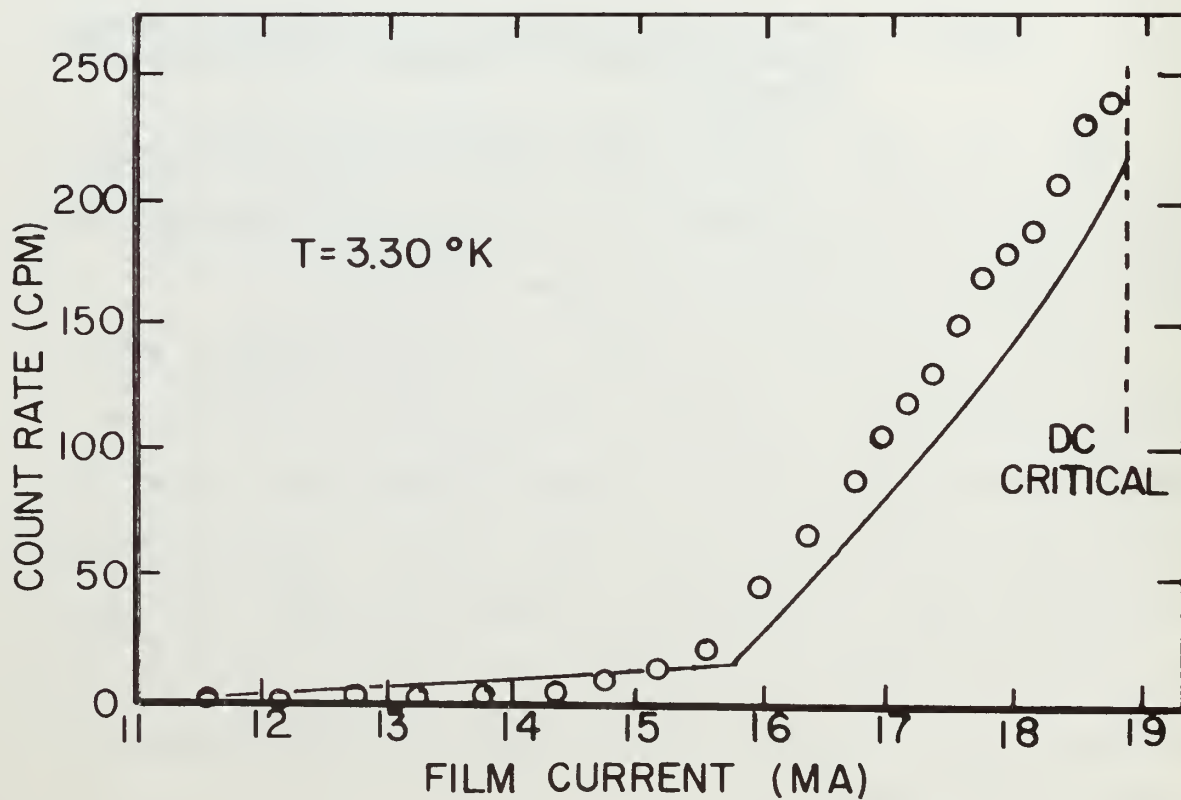
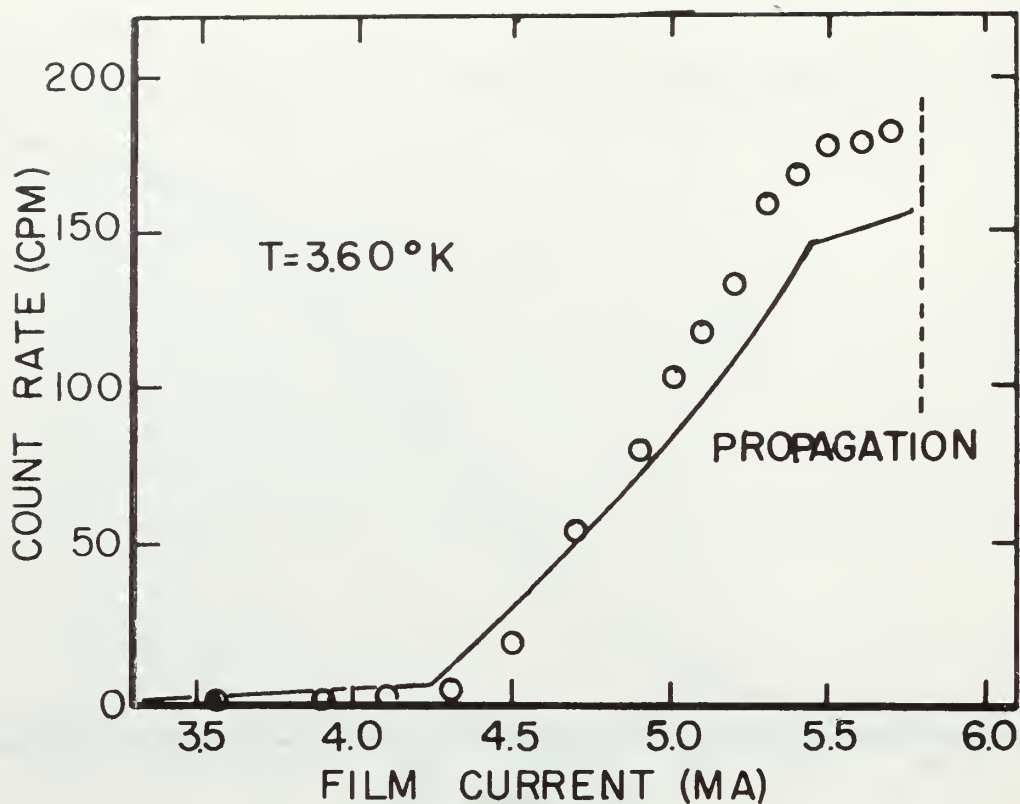


Fig. 17. Experimental and Theoretical Count Rate Versus Current Curves.

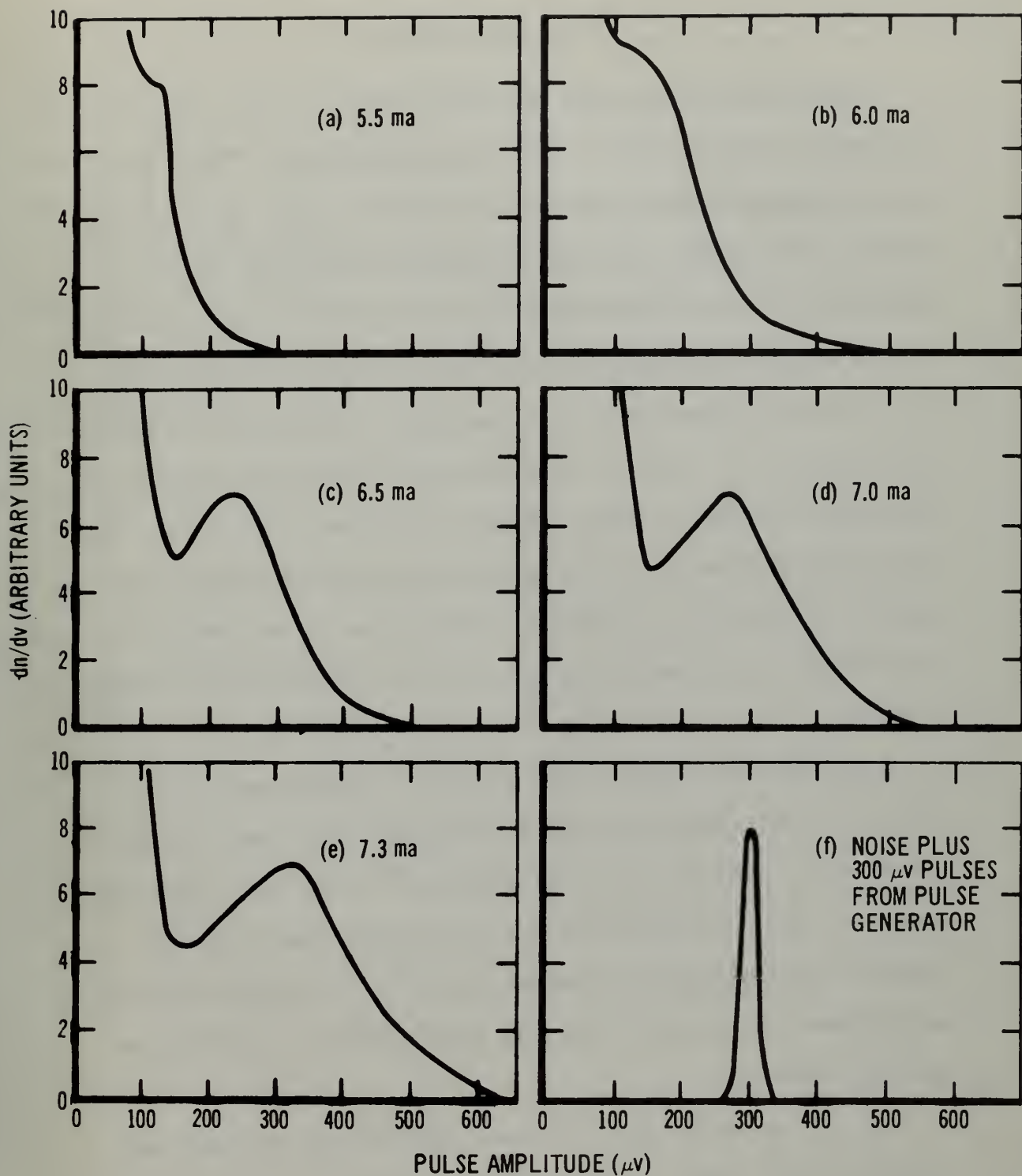


Fig. 18. Pulse Height Distributions as a Function of Film Current for a 33 Micron Wide Tin Film at 3.60°K.

#### IV. CONCLUSIONS

These experiments have demonstrated that superconducting, thin films can be used to detect alpha particles. Both self-recovering and propagating pulses were observed. It is noteworthy that the self-recovering pulses can be very fast, approaching a few nanoseconds duration at low current densities. It was shown, too, that if the film is in direct contact with its substrate, then the latter can play a significant role in pulse formation. Thin, insulating films interposed between the detectors and their substrates were effective in thermally decoupling the detector. The insulating layers provided an impedance mismatch to the phonons originating in the substrate, permitting only a small fraction of the incident phonon energy to pass.

The effective radii of the regions driven normal by the passage of an alpha particle were measured and these values compared to those derived from solutions to the heat diffusion equation. And, although the use of classical heat flow to describe the phenomenon appeared marginal, the substantial agreement between the results and this theory seems to justify the approach taken.

The variation of count rate with current was studied and compared with a model based upon the variation of critical current with position along the film. Again there is significant agreement, and this agreement lends credence to the manner in

which the effective radii were measured. In this context, an experiment in which the alpha beam was sharply collimated and swept slowly down the length of the film would provide a direct measure of  $I_a(x)$ , and would yield interesting data on  $I_c(x)$ .

Finally, although only alpha particles were employed in these experiments, the application of these techniques to the detection of other charged particles, fission fragments for example, would seem justified.



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| 13. ABSTRACT<br>The response of thin, superconducting films of tin and of indium to alpha particle bombardment has been studied. The films were sufficiently thin and narrow that individual alpha particle impacts initiated superconducting to normal transitions across a full film cross section. The transitions were observed by means of the IR drop produced by a transport current. For low current densities, self-terminating voltage pulses of a few nanoseconds duration were observed. At higher current densities, a normal region initiated by an alpha particle propagated, by Joule heating, to the ends of the film. The alpha-particle range exceeded the thickness of the films and the energy deposited in the substrate by an alpha traversal affected the response of any film in direct contact with its substrate. Thin, thermally insulating films introduced between the detectors and their substrates, however, effectively isolated the detectors. The variation of count rate with film current was studied and is shown to be consistent with the variation of critical current density along the length of the film. A heat diffusion model accounts for the observed behavior of the thermally isolated films. |  |                                                                                             |                       |

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## KEY WORDS

## LINK A

## LINK B

## LINK C

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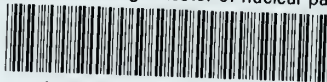






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